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Roland Alonso[a]*, Mickaël Causse[b], François Vachon[c], Robert Parise[a], Frédéric Dehais[b] and Patrice Terrier[d]

[a]*DSNA, DTI R&D, Toulouse, France;* [b]*ISAE, Université de Toulouse, Toulouse, France;* [c]*Université Laval, Québec, Canada;* [d]*Université Toulouse Le-Mirail, Toulouse, France*

The purpose of this study was to investigate the possibility to integrate a free head motion eye-tracking system as input device in air traffic control (ATC) activity. Sixteen participants used an eye tracker to select targets displayed on a screen as quickly and accurately as possible. We assessed the impact of the presence of visual feedback about gaze position and the method of target selection on selection performance under different difficulty levels induced by variations in target size and target-to-target separation. We tend to consider that the combined use of gaze dwell-time selection and continuous eye-gaze feedback was the best condition as it suits naturally with gaze displacement over the ATC display and free the hands of the controller, despite a small cost in terms of selection speed. In addition, target size had a greater impact on accuracy and selection time than target distance. These findings provide guidelines on possible further implementation of eye tracking in ATC everyday activity.

**Practitioner Summary**: We investigated the possibility to integrate a free head motion eye-tracking system as input device in air traffic control (ATC). We found that the combined use of gaze dwell-time selection and continuous eye-gaze feedback allowed the best performance and that target size had a greater impact on performance than target distance.

**Keywords:** eye tracking; air traffic control; gaze selection; Fitts' law

## Introduction

The main purpose of air traffic control (ATC) worldwide is to optimise the flow of traffic and to separate aircraft to prevent collisions both in the air and on the ground. To do so, air traffic controllers use both pieces of paper called 'strips' or interact with a classical mouse on their radar screen to store relevant information (e.g. aircraft speed and altitude). The aim of such record is to ensure an accurate situation awareness of traffic flow. In a near future, paper strips will likely disappear and controllers will then have to rely exclusively on electronic systems to store relevant information. Hence, research is required in order to examine other possibilities to interact with such technologies to enhance controller abilities. For instance, an experiment showed that tablet computers can be successfully employed to select radar label displayed on the radar screen (Alonso et al. 2009). The aim of this study was to test the potential contribution of eye-tracking technology to supporting air traffic controllers' operations.

Eye tracking is now commonly found in experiments in the field of aeronautics. For instance, it has been used to assess mental workload in ATC activity (Ahlstrom and Friedman-Berg 2006) or to better understand emotion effects on pilot's decision-making (Causse et al. 2011). One reason that makes eye-tracking techniques so attractive in the context of ATC is that they offer the opportunity to totally free the hands of controllers. Freeing the controller's hands could allow him/her to manipulate strips (paper or electronic) without disturbance, and provides the opportunity to use more easily new technologies and interfaces currently developed in the air traffic domain (Hurter et al. 2012). Having hands free would also help preventing repetitive strain injury, known to be caused by the recurring operation of mechanical input devices (Bates 2002). Another reason why eye tracking is appealing is that eye movements are fast and natural. For instance, eye-gaze interaction has been shown to speed up the selection of information relative to other input media such as the mouse (Sibert and Jacob 2000). This is because the user's gaze is often already fixated on the target long before the cursor homes in. There is empirical evidence that eye trackers can become an efficient pointing device that can be used instead of the mouse (Majaranta et al. 2006; Zhai, Morimoto, and Ihde 1999) or the keyboard (Bee and André 2008; Haffegee and Barrow 2009; Kotani et al. 2010). For instance, a recent study of Jochems, Vetter, and Schlick (in press) demonstrated the advantages of the combination of eye-gaze designation and separate target confirmation with the space bar of a keyboard in elderly people with motor impairments. Other authors (Lin et al. 2011) showed that eye-gaze interactions can be used in systems for the

*Corresponding author. Email: roland.alonso@egis.fr

general public (museum), the computer produced speech according to the location of user's gaze and enhanced the quality of the interactions.

Beyond the controlled experimental research on eye-gaze control, several studies highlight the benefits of using gaze control interface in various operational settings. For instance, Merchant and Schnell (2000) proposed to use eye-tracking input method in pilots for the activation of controls and functions in commercial aircraft flight decks in order to reduce the effort of interaction with the system (e.g. knobs, levers and so on). In medicine, some studies revealed promising outcomes of using real-time gaze control to define a robot trajectory during robotic-assisted minimally invasive surgery (Mylonas, Darzi, and Zhong Yang 2006; Noonan et al. 2008, 2010). A gaze-control approach has also been successfully adopted in the teleoperation domain by Zhu, Gedeon, and Taylor (2011). In that study, operators controlled a remote camera with eyes while carrying out other actions in a modelled hands-busy task. The authors found that gaze-driven control significantly outperformed the conventional joystick control, as showed by both the operators' objective behavioural performance and subjective feelings.

Despite the potential benefits of using eye tracking as an input device instead of conventional hand-based methods, no studies attempted, to our knowledge, to verify whether the advantages of such technology can be applied for assisting air traffic controllers. Moreover, because eye tracking requires special hardware and software, research is required to determine whether this technique is worth the extra effort. Therefore, this study examined the possibility to integrate a free head motion eye-tracking system as a substitute to traditional manual input device in ATC by performing experiments with standard radar screen. Given the safety-critical nature of ATC, factors relating to the reliability and accuracy of eye-tracking systems need to be considered in the implementation of such technology as an input method for air traffic controllers. Accuracy of eye trackers is continuously improving but these systems are still not perfect, calling for the presence of on-line visual feedback. Inaccuracy originates partly from eye-tracking systems' limitation and partly from features of the eye (Jacob 1995). Majaranta et al. (2006) examined the impact of a discrete form of feedback which consists in highlighting the target under the focus of the gaze. In the context of a typing task with a virtual keyboard, the authors found that highlighting the key the participant was looking at improved both accuracy and speed of typing. However, given that this method does not provide any feedback on the estimated eye position when the gaze is not located on a relevant target, it may not be suitable for ATC as targets displayed on the radar screen are usually more sparse than the keys of a computer keyboard and their spatial location is constantly changing. Continuous eye-gaze feedback with the visual cursor could constitute a better candidate for ATC as it facilitates the control of gaze displacement over the visual display and may constantly reduce uncertainty regarding the estimated gaze position (Jacob 1995). Such feedback may improve accuracy as it allows the user to correct online an offset of the cursor location with the real gaze position effect. However, in addition to its potential attention–attraction power, continuous eye-gaze feedback may be susceptible to calibration errors, whereby a slight offset of the cursor location with the real gaze position could provoke an incessant pursuit of the cursor for the user (Jacob 1995). This is the form of feedback we examined in this study.

Another important factor that can influence the reliability of eye tracker as an input device for ATC is how target information can be selected on the display. Different eye-tracking inputs, such as eye blink or dwell time, have been considered to select objects on a user interface. Eye blinks as a signal are unsatisfactory because they detract from the naturalness possible with an eye movement-based dialogue by requiring the user to think about when to blink (Jacob 1995). Whereas one can favour the dwell-time method over selection by blinking because it is viewed as a rather natural way of selecting information (Jacob 1993), it also forces the user to be constantly conscious of where he/she is looking and how long he/she is looking at an object. Indeed, with the dwell-time technique, the user must fixate an object long enough (e.g. 400 ms) to avoid missed selection while at the same time avoiding lengthy fixation over irrelevant objects in order to prevent unintentional selection (Zhai, Morimoto, and Ihde 1999). To circumvent dwell time issue, Zander et al. (2010) developed a multimodal interface using eye movements to determine the object of interest and an electroencephalographic brain–computer interface (BCI) to simulate the activation command. Results show that the resulting hybrid BCI was a robust and intuitive device for touchless interaction. Although selection times were slower than standard dwell time eye-gaze interfaces, it reliably leads to fewer errors.

Zhai, Morimoto, and Ihde (1999) proposed a mixed approach combining the automatic warping of the cursor position near the probable gazed target with the manual validation with the computer trackpoint. Although this hybrid technique appeared beneficial with regard to the user effort – it reduced manual pointing movements – it provided no obvious advantage in terms of selection speed, in accordance with Zander et al's. study. Yet, speed of use is one of the key interests of using an eye tracker as an input device. Nonetheless, the assertion that the interaction with an eye tracker would necessarily lead to faster selection remains uncertain. This is especially true when considering the potential effects of target size and target-to-target distance, two factors linked to task difficulty. Ware and Mikaelian (1987) established that gaze selection time follows Fitts' law (1954), a logarithmic function of distance when target size is held constant and a logarithmic function of target size when distance is held constant. Surakka, Illi, and Isokoski (2004) also found that gaze selection time is a function of Fitts' law, but to a lesser extent than selection time with a mouse. Interestingly, Sibert and

Jacob (2000) showed that gaze selection time lengthened only slightly with target-to-target distance, which suggests that eye-gaze selection could be very useful for displays entailing longer-distance cursor movements such as ATC radars.

Given the dearth of studies that have used a head-free eye tracker in the ATC context, this study aimed at providing insights into the reliability of eye-tracking systems in assisting the air traffic controller in his/her interactions with ATC radar monitor. To determine whether this technology is accurate enough to support the selection of small flight labels, we tailor-designed an experiment in which we assessed the effects of eye-gaze feedback and selection method on gaze target selection performed with a head-free eye tracker. Because of its potential advantages in ATC context, we examined the impact of continuous visual eye-gaze feedback relative to the absence of any feedback. To our knowledge, this was the first time such comparison was performed on eye-gaze selection performance as gaze feedback is usually either provided (Miniotas 2000) or not (Zhang and MacKenzie 2007). Due to the well-known limitations in terms of precision of head-free eye trackers, we expected better selection performance (i.e. faster and more accurate target selections) in the presence of continuous feedback. In order to verify whether controllers can interact efficiently with radars without the help of an additional selection device (mouse or a keyboard), we contrasted the traditional key-press selection to the dwell-time technique. In this experimental context, the latter technique required participants to fixate a target for 500 ms to select it, which was expected to slow down the selection process relative to the key-press method. Given that target selection is influenced by how targets are displayed (e.g. Surakka, Illi, and Isokoski 2004; Ware and Mikaelian 1987), we also manipulated target size and target-to-target separation, hence inducing various levels of difficulty following Fitts' law. Such manipulation permitted to determine to what extent feedback and selection method efficiency rely on difficulty level, which should help providing insights into the optimal configuration of ATC displays for eye-gaze information selection.

## Method

### *Participants*

Sixteen participants (four females), ranging from 24 to 42 years of age ($M = 34.1$ years; SD $= 4.7$), were recruited by local advertisement. They had no prior experience with eye-tracking technology and they all reported normal uncorrected vision. Participants gave their informed consent after receiving complete information about the nature of the experiment. They were randomly assigned to one of two groups: with feedback ($N = 7$) and without feedback ($N = 9$).

### *Apparatus*

Participants were seated in front of an 18-in ATC radar monitor (1280 × 1024 pixels) located at a distance of 80 cm from their head (Figure 1). This monitor is being used by air traffic controllers in their everyday activity. A keyboard was placed at the centre of the desk and was used during the key-press condition. The *faceLAB 4* eye tracker (Seeing Machines, Inc.) was used with a sampling rate of 60 Hz and 1° of accuracy. The measurement method was pupil and corneal reflection. Two infrared cameras located in front of the participant were set to focus the participant eyes.

### *Design and procedure*

Participants were asked to perform eye-pointing movements with different amplitudes and target sizes as fast and accurately as possible. On each trial, a white circle (target) was displayed on a black background. On each trial, participants had to move their gaze inside the target. In key-press condition, participants validated the fixated target by pressing a key on a keyboard. In the dwell-time condition, the validation of the target occurred when participants fixated the target during 500 ms. A target was considered as missed when the selection was performed while the gaze was outside the target area. Following the selection, the target turned either to green if successfully selected or to red if missed. After each selection, another target automatically appeared at a predetermined location on the screen and the participant had to select it according to the current selection method. Participants from the feedback group performed all trials with continuous eye-gaze feedback, which consisted of a cursor displayed on the monitor that continuously indicated the real-time gaze position estimated by the system. In the no feedback group, no such feedback was provided.

All participants were subjected to nine levels of difficulty based on Fitts' law according to the Shannon formula (see MacKenzie 1992):

$$\mathrm{MT} = a + b\log_2\left(1 + \frac{D}{W}\right), \tag{1}$$

where MT represents the mean movement time, $a$ represents the start/stop time and $b$ stands for the inherent speed of the device (slope). These constants are experimentally determined by fitting a straight line to the measured data. $D$ represents

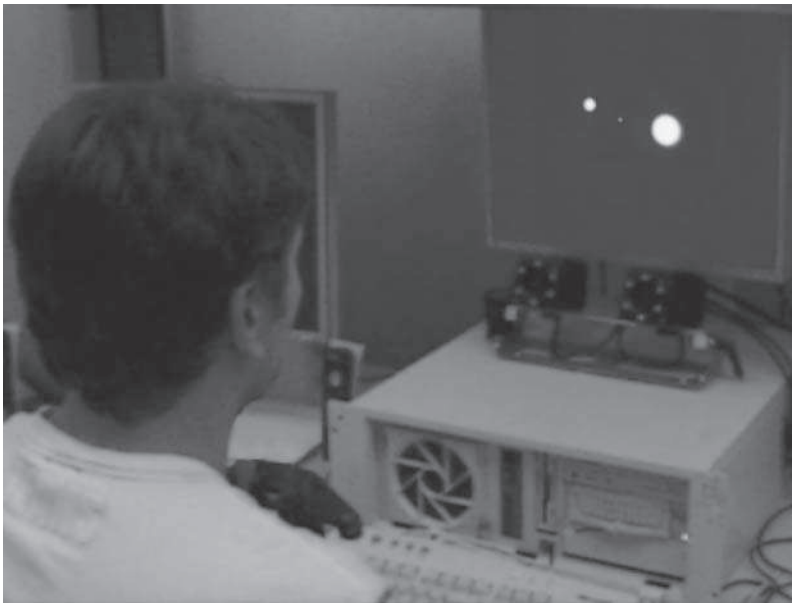

Figure 1. Experimental set-up. The eye tracker was placed below the screen and the keyboard in front of the participant. On the screen, the gaze was moving from the large target (5 cm) to the small target (2 cm), as indicated by the cursor provided in the continuous visual feedback condition. In this example, the target-to-target distance was 15 cm.

the distance from home position to the centre of the target and $W$ is the width of the target. The term $\log_2\left(1+(D/W)\right)$ is the index of difficulty level for the target. Difficulty was founded on the combination of pairs among three targets diameters (2, 3 and 5 cm) and three target-to-target separations (5, 15 and 30 cm). Target-to-target separation was computed between the centre of the to-be-selected target and the centre of the just-selected target. Difficulty level was expressed in bits and the built combinations are displayed in Table 1.

The three main independent variables yielded a $2 \times 2 \times 9$ mixed design with Feedback (with vs. without) as a between-subjects factor, and selection method (key press vs. dwell time) and difficulty level (nine levels) as within-subject factors. Following 34 practice trials, participants performed 612 trials, that is 34 trials for each of the 18 combinations of selection method and difficulty level. Participants performed the task either with or without continuous feedback. Each group performed two blocks, one with the dwell-time technique and the other with the key-press selection method; the order of these blocks being counterbalanced across participants. In each block, target size and target-to-target separation varied randomly.

Table 1. Levels of difficulty (bits) implemented in this study using Fitts' law with associated target size (in cm and °) and target separation (in cm and °). Angles were computed based on a distance of 80 cm from the screen.

| Difficulty level | Difficulty (bits) | Target size (cm/°) | Target-to-target separation (cm/°) |
|---|---|---|---|
| 1 | 1 | 5/3.57 | 5/3.57 |
| 2 | 1.41 | 3/2.14 | 5/3.57 |
| 3 | 1.80 | 2/1.43 | 5/3.57 |
| 4 | 2 | 5/3.57 | 15/10.71 |
| 5 | 2.58 | 3/2.14 | 15/10.71 |
| 6 | 2.80 | 5/3.57 | 30/21.23 |
| 7 | 3.08 | 2/1.43 | 15/10.71 |
| 8 | 3.45 | 3/2.14 | 30/21.23 |
| 9 | 4 | 2/1.43 | 30/21.23 |

## Results

Two dependent variables were computed and analysed: target selection time – i.e. the time required to select the target after its onset – and selection accuracy (a selection performed while the gaze was outside the target area was considered as miss whereas a selection performed while the gaze was inside the target area was recorded as a hit). Analysis of target selection time was restricted to those trials for which a correct selection was recorded. The Kolmogorov–Smirnov goodness-of-fit test showed that the two dependent variables distributed normally; therefore, a mixed analysis of variance (ANOVA) was performed on each performance measure. Tukey's HSD (Honestly Significant Difference) was used for post-hoc comparisons. The alpha level was set at 0.05.

### *Accuracy*

Figure 2 presents mean percentage of correct selection as a function of the difficulty level in the selection method (dwell time vs. key press) and feedback (with or without) conditions. The $2 \times 2 \times 9$ mixed ANOVA carried out on these data revealed a significant main effect of all three factors: difficulty level, $F(8, 112) = 36.31$, $p < 0.001$, $\eta_p^2 = 0.712$; selection method, $F(1, 14) = 11.20$, $p = 0.005$, $\eta_p^2 = 0.444$, indicating higher accuracy with the dwell-time technique; and feedback, $F(1, 14) = 6.83$, $p = 0.020$, $\eta_p^2 = 0.330$, showing better performance in the presence of feedback. The significant interaction between selection method and feedback, $F(1, 14) = 18.94$, $p < 0.001$, $\eta_p^2 = 0.574$, arose because accuracy improved in the presence of feedback with the key-press method ($p < 0.001$) but not with the dwell-time technique ($p = 0.523$). Finally, difficulty level interacted significantly with all other factors: selection method × difficulty level, $F(8, 112) = 2.90$, $p = 0.006$, $\eta_p^2 = 0.172$; feedback × difficulty level, $F(8, 112) = 2.74$, $p = 0.008$, $\eta_p^2 = 0.164$ and selection method × feedback × difficulty level, $F(8, 112) = 3.91$, $p < 0.001$, $\eta_p^2 = 0.218$. These results point towards a stronger beneficial effect of feedback on accuracy for difficulty levels involving small targets, especially with the key-press method.

Interestingly, it is obvious from the visual inspection of Figure 2 that accuracy did not decrease linearly with the level of difficulty. We observed significant improvement in correct target selection from level 3 to level 4, from level 5 to level 6 and from level 7 to level 8 ($p < 0.001$), that is each time the increase in difficulty level was associated with an increase in target size. Given such findings suggest a larger influence of target size on accuracy over target-to-target separation, we analysed separately the impact of target size and target-to-target separation on target selection time with no regard to feedback and selection method. The results are plotted in Figure 3. A 3 (target size: 2, 3 and 5 cm) × 3 (target-to-target separation: 5, 15 and 30 cm) repeated-measures ANOVA performed on these data revealed a significant main effect of target size, $F(2, 30) = 56.08$, $p < 0.001$, $\eta_p^2 = 0.789$, an indication that accuracy increased with target size. However, target-to-target separation failed to influence selection precision as suggested by the absence of significant main effect of target-to-target separation, $F(2, 30) = 2.20$, $p = 0.128$, $\eta_p^2 = 0.128$, and two-way interaction, $F(4, 60) < 1$, $p = 0.841$, $\eta_p^2 = 0.023$.

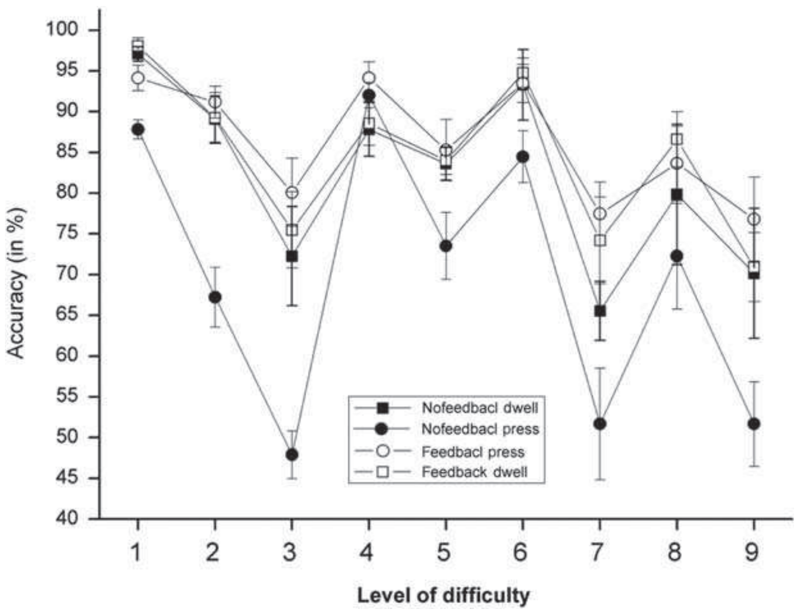


Figure 2. Mean percentage of correct selection as a function of difficulty level (1–9, based on Fitts' law) and feedback (with or without) in the dwell-time and key-press conditions. Error bars represent the standard error of the mean.

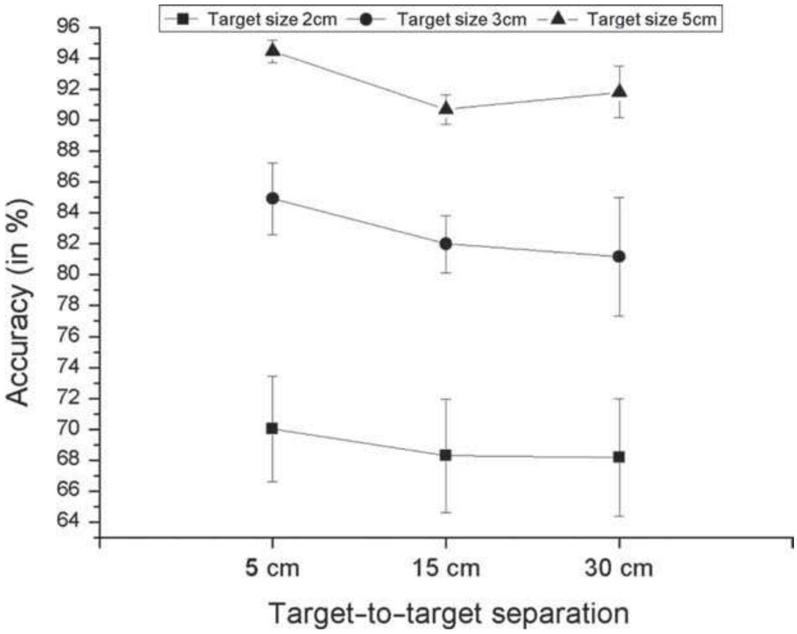


Figure 3. Mean percentage of correct selection as a function of target-to-target separation and target size. Error bars represent the standard error of the mean.

### *Target selection time*

*Fig*ure 4 presents mean target selection time (s), given correct selection, as a function of the difficulty level in the selection method (dwell time vs. key press) and feedback (with or without) conditions. The $2 \times 2 \times 9$ mixed ANOVA carried out on these data revealed a main effect of selection method, $F(1, 14) = 13.61$, $p = 0.002$, $\eta_p^2 = 0.493$, indicating, as expected, that selection was slower with the dwell-time technique ($M = 1.19$ s, $SE = 0.035$) than when using the key-press method ($M = 0.98$ s, $SE = 0.075$). The main effect of difficulty level was significant, $F(8, 112) = 46.07$, $p < 0.001$, $\eta_p^2 = 0.767$, whereas that of feedback was not, $F(1, 14) < 1$, $p = 0.334$, $\eta_p^2 = 0.064$. Nevertheless, the effect of feedback was modulated by difficulty level, $F(8, 112) = 2.67$, $p = 0.010$, $\eta_p^2 = 0.160$, as the presence of feedback tended to lengthen mean selection

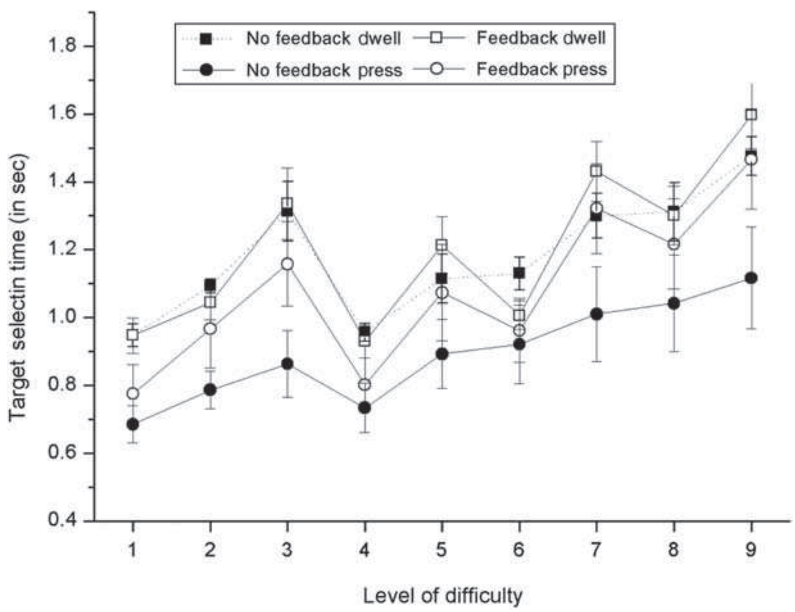


Figure 4. Mean target selection time (s), given correct selection, as a function of difficulty level (1–9, based on Fitts' law) and feedback (with or without) in the dwell-time and key-press conditions. Error bars represent the standard error of the mean.

time at difficulty levels 7 and 9 (with the smallest target size) relative to the absence of feedback. None of the remaining interaction effects reached significance ($F < 2.38$, $p < 0.15$).

A visual inspection of Figure 4 reveals that the effect of difficulty level on target selection time was not linear, suggesting that selection time – as for selection accuracy – did not follow Fitts' law. Indeed, significant improvements in selection time were found with increases in difficulty from level 3 to level 4 as well as from level 5 to level 6 ($p < 0.001$), that is when target size increased to its largest size (5 cm; Table 1). Such a result points towards a larger influence of target size on selection time over target-to-target separation. Consequently, we analysed separately the impact of target size and target-to-target separation on target selection time with no regard to feedback and selection method. The results are plotted in Figure 5. The $3 \times 3$ repeated-measures ANOVA performed on these data revealed significant main effects of target size, $F(2, 30) = 90.83$, $p < 0.001$, $\eta_p^2 = 0.858$, and target-to-target separation, $F(2, 30) = 30.47$, $p < 0.001$, $\eta_p^2 = 0.670$, indicating that selection time increased as target size decreased and as target-to-target separation increased. Partial $\chi^2$ (0.86 vs. 0.67) suggests that the effect of target size on selection time was stronger than that of target-to-target separation. In addition, the two-way interaction approached significance, $F(4, 60) = 2.14$, $p = 0.086$, $\eta_p^2 = 0.125$. This interaction almost arose because the increase in selection time with target-to-target separation tended to be limited to the largest separation (30 cm) when the target was at its biggest size (5 cm; Figure 5). Post-hoc test showed no significant effect of increased target-to-target separation on target selection time (for 5 cm target size only) between 5 versus 15 cm target separation ($p = 0.999$), whereas the comparison between 15 versus 30 cm target-to-target separation revealed a significant impact on target selection time ($p < 0.001$). This suggests that the negative impact of target-to-target separation on selection time can be reduced by using sufficiently large targets.

## Discussion

The main purpose of this study was to assess the usability of a free head-motion eye-tracking system as an input device in ATC activity. Within the context of eye-gaze selection of target information on an ATC monitor, we contrasted selection validation through a key press to an eye-tracking dwell-time selection technique. This comparison was made in the presence or absence of continuous feedback about gaze position on the display under various levels of difficulty induced by varying target size and target-to-target separation. Overall, the dwell-time technique produced slower but more accurate target selection than key press, at least without any feedback. When continuous feedback about gaze position was provided, the accuracy superiority of the dwell-time method vanished. With mean accuracy levels as high as 95% correct and mean selection times that could go below 1 s, the eye tracker seems to have the potential to be an effective hand-free input device for air traffic controllers, especially when considering that participants were asked to perform the selections as fast as possible and that rather small targets (2 cm) were used in this study.

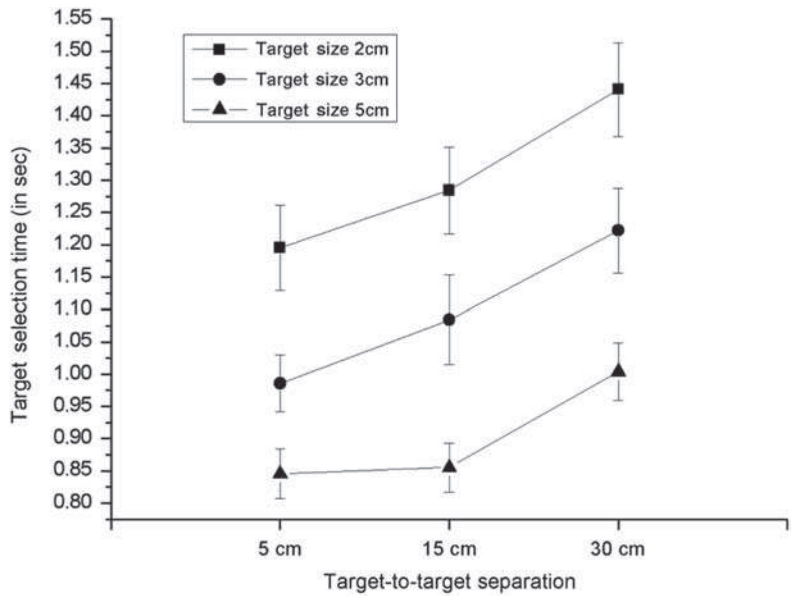


Figure 5. Mean target selection time (s), given correct selection, as a function of target-to-target separation and target size. Error bars represent the standard error of the mean.

As expected, the results showed that validating target information with prolonged eye fixation took more time than doing so with a key press. This is probably because participants had to fixate the target during 500 ms to select it with the dwell-time technique, whereas with the key-press method, they could validate the target as soon as they estimated their gaze was located on the target. Given that selection accuracy was similar with both techniques in the presence of continuous feedback, the key-press method appears to be the selection procedure offering the best speed/accuracy tradeoff. At first blush, such a conclusion suggests that despite the introduction of an eye-tracking system in the controller's operations, the use of a tangible input device (e.g. keyboard and mouse) would still be recommended for interacting with the ATC radar monitor. Nevertheless, it is worth noting that the increase in selection time associated with the dwell-time method, though statistically significant, was rather small (1.20 s vs. 1.08 s with key press) in the presence of continuous visual feedback. On that account, such a small cost in terms of speed of operation is certainly compensated for by the advantage of freeing the controller's hands conferred by the eye-gaze dwell-time selection method.

Moreover, the dwell-time technique showed the best accuracy level in the absence of feedback about gaze position. This could be attributable to the fact that with this procedure, both (gaze) displacement over the display and target selection were performed using the same gaze-based processes, whereas key-press selection involved hand-based processes different in nature from those required to move a 'virtual' cursor on the screen. Besides, when a proper visual cursor was provided in the form of continuous feedback, accuracy improved with the key-press technique up to the level observed with the dwell-time method, probably because the constant visual cues helped coordinating limb actions and gaze control. Indeed, it is possible that the need to press a key while having to concurrently fixate a specific area on a display induced a transient loss of gaze control provoking small shifts in gaze position. In line with this idea, the presence of feedback was associated with prolonged selections when difficulty was high and target size small (i.e. 2 cm), especially in the key-press condition (Figure 5). Most likely, this increase in selection time was linked to final error-correcting secondary saccades (Wu, Kwon, and Kowler 2000) that allowed adjusting the cursor within the target to correct any shift between the actual position of the gaze and the targeted location.

An important issue is to clarify whether making eye movement a functional part of manipulating the user interface can influence the information perception function of vision. Indeed, using visual perceptual system as an input channel is not without consequence. Moving one's eyes is often an almost subconscious act and can be interpreted as an indication of what the user is currently paying attention to, without any explicit input action on his part (Rayner 2009). People may expect to be able to look at an item without necessarily triggering an action (Zander et al. 2010). The users may constantly avoid lengthy fixation over irrelevant objects in order to prevent unintentional selection, what could alter visual processing and promote inattentional blindness (Simons 2000). Even if our study revealed that the dwell-time method offers good performance, this shift from an automatic and unconscious ocular behaviour to a controlled and conscious one may hinder the benefits of freeing the hands in some individuals. In this sense, keeping the possibility to use a separate validation channel could bring a good compromise.

The present results indicated that, although gaze selection performance tended to decrease as the level of difficulty increased, neither accuracy nor selection time evolved in a linear fashion with difficulty level, suggesting that Fitts' law does not fully apply to eye-gaze selection. Such findings contradict previous studies showing that gaze selection time typically follows Fitts' law (Sibert and Jacob 2000; Surakka, Illi, and Isokoski 2004; Ware and Mikaelian 1987). To manipulate task difficulty according to Fitts' law, we varied the size of the targets as well as the target-to-target distance. The results clearly showed that target size matters more than target-to-target distance for time-pressured gaze selection: target-to-target distance only impacted selection time and its influence was reduced by target size. The fact that eye movements are extremely fast (e.g. Boghen et al. 1974) is consistent with the finding that target-to-target distance played only a small role in this study (see also Sibert and Jacob 2000). Our results suggest that increasing target size can lead to interesting improvements in selection performance, in terms of both accuracy and speed. Accordingly, small targets (e.g. 2 cm) are not recommended in ATC settings as they require high-gaze precision and can provoke an important increase of time-consuming error-correcting secondary saccades (Wu, Kwon, and Kowler 2000). Instead, the implementation of an eye-tracking input device in ATC activity would require the display of target objects large enough to optimise selection precision and speed. According to the present findings, such large targets would also reduce the negative impact of having important target-to-target distance on the display.

This study confirmed that although the overall accuracy level was rather high, systems are still not perfect, calling for the presence of on-line visual feedback (Jacob 1995). Yet, even seldom mis-selections in the context of real ATC activity could have dramatic consequences. Indeed, most likely, in some cases, the participant perfectly gazed inside the target but that a slight offset between the real participant gaze position and that estimated by the system led to an incorrect selection. Consequently, before implementing eye-tracking input systems within ATC towers, it would be important to test whether other free head-motion eye-tracking systems can promote near-perfect target selection.

One limitation of this study is the absence of a 'control' condition in which target selection is made using a conventional input device such as a mouse or a keyboard. This omission – due to practical reasons with regard to the addition of further participants – precludes any direct comparison between eye-tracking techniques and traditional hand-based controls that would allow us to set the former in relation to the latter. Nevertheless, a look at recent literature suggests that eye tracking can be as efficient as the mouse for input control, at least under certain conditions. For instance, Tall et al. (2009) found that gaze control of a remote vehicle driving made with a high-precision – but not a low-precision – eye tracker was similar to mouse control. In the context of target selection on a visual display, MacKenzie (2012) showed that a gaze-based input device allows for satisfactory performance in terms of selection speed and accuracy, but this performance is not as good as that observed with the mouse. As in the study of Tall et al. (2009), the quality of the eye-tracking system appears to be crucial as MacKenzie identified eye jitter and limitations in the eye tracker's accuracy as the main causes of the longer selections found with the eye tracker relative to the mouse. With regard to accuracy, it is noteworthy that the targets used by MacKenzie were very small (the larger target had a diameter of only 12 mm) compared to those employed in this study (the smallest target had a diameter of 2 cm). Given that we showed that gaze-based selection accuracy levels acceptable for ATC can be reached with relatively large targets (i.e. at least 3 cm), MacKenzie's findings should not be taken as hard evidence for the superiority of the mouse over the eye tracker in target selection, at least in the context of ATC.

It is worth noticing that eye tracking could also bring clues on controller's objective internal state through pupil diameter (Causse et al. 2012; de Greef et al. 2009), saccadic activity (Ahlstrom and Friedman-Berg 2006) and eye blink measurements (Brookings, Wilson, and Swain 1996). This may help to adjust the controller's mental workload, for instance with an online adjustment of the number of aircraft to control. The triggering of such adaptive automation may help to prevent decisional errors, in response to cognitive overload, stress or fatigue. In addition, the online real time localisation of the operator gaze gives the opportunity to display messages and/or alerts precisely under its current visual focus. This method would be a powerful mean to ensure that critical information is not unnoticed simply because the current point of fixation is too far from the notification.

To summarise, the use of an eye-tracking system as an input device in ATC activity appears promising. The precision and speed of selecting target information entailed by the eye tracker were acceptable in this study and can surely be improved. Among the approaches available to select information, we could tend to favour the dwell-time method over the key-press technique as it suits naturally with gaze displacement over the ATC display and free the hands of the controller, despite a small cost in terms of selection speed. Although the presence of continuous visual feedback about gaze position did not significantly improve dwell-time selection performance (but it did for key-press selection), such feedback could nonetheless be provided as it did not seem to impede the selection process. Finally, the size of target information appears to be an important factor to consider when using an eye tracker to support controllers' operations, as large targets were associated with faster and more accurate selections. Hence, the future use of such a system in ATC activity would require an adjustment of items size in human–computer interface used by air traffic controllers in order to reach a satisfying level of efficiency and reliability. Although ensuing from a simplified version of an ATC task, the present findings suggest that the removal of a tangible selection device in ATC could be possible in a near future. Nevertheless, as long as the unintentional selection issue associated with the dwell-time method is not perfectly solved, it may be sagacious to allow the controller to choose the selection technique between key press and dwell time he/she is more comfortable with.

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